Nonstandard Interaction in ν_τ-nucleon scattering

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The effects of nonstandard interaction (NSI) on neutrino oscillation have been widely studied [1]. General bounds on the NSI parameters have been discussed in the literatures [2]. The NSI impact has been studied on different themes in neutrino phenomenology [3]. Often in the analysis of NSI, hadronization effects of the quarks via form factors are not included. In Ref. [4, 5], the results show that the form factors play an important role in the energy dependence of the NSI effects.

The charged Higgs and W' gauge boson contributions to the quasielastic scattering (QE), Δ-resonance production (Δ-RES) and deep inelastic scattering (DIS) in the interactions

$$
\begin{aligned}
\nu_\tau + N &\to \tau^- + X, \\
\bar{\nu}_\tau + N &\to \tau^+ + X,
\end{aligned}
\tag{1}
$$

have been discussed in Refs.[4, 5]. Here $N = p, n$ is a nucleon and X is the possible final state where $X = p, n$ in the QE and, in particular, $X = \Delta$ states in the Δ-RES. In the neutrino oscillation experiments, the neutrino-nucleus interaction at the detection process is assumed to be SM-like in the relationships [6]:

$$
\begin{aligned}
N(\nu_\tau) &= P(\nu_\mu \to \nu_\tau) \times \Phi(\nu_\mu) \times \sigma_{\mathrm{SM}}(\nu_\tau), \\
N(\bar{\nu}_\tau) &= P(\bar{\nu}_e \to \bar{\nu}_\tau) \times \Phi(\bar{\nu}_e) \times \sigma_{\mathrm{SM}}(\bar{\nu}_\tau),
\end{aligned}
\tag{2}
$$

that could be used in atmospheric and reactor experiments, respectively. Here $N(\nu_\tau)$ is the number of observed events, $\Phi(\nu_\mu)$ is the flux of muon neutrinos at the detector, $\sigma_{\mathrm{SM}}(\nu_\tau)$ is the SM cross section of tau neutrino interaction with nucleons at the detector, and $P(\nu_\mu \to \nu_\tau)$ is the probability for the flavor transition $\nu_\mu \to \nu_\tau$. Corresponding definitions are used in the second equation in Eq. 2. The extracted neutrino mixing angles, using the SM cross section, will have errors if there are NP effects. The NP effects modify the standard model cross section for the above processes. Therefore, the NP effects impact the extraction of the atmospheric and reactor neutrino mixing angles θ_{23} and θ_{13}, respectively, when they are measured via the detection of $\nu_\tau(\bar{\nu}_\tau)$ through the processes in Eq. 1. The form factors are used in the QE and Δ-RES calculations.

The reactions in Eq. 1 are relevant to experiments like Super-Kamiokande (Super-K) [7] and OPERA [8] that seek to measure $\nu_\mu \to \nu_\tau$ oscillation by the observation of the τ lepton. If the reactor neutrino experiments are designed to measure the tau antineutrino appearance $\bar{\nu}_e \to \bar{\nu}_\tau$, the process $\bar{\nu}_\tau + N \to \tau^+ + X$ will be important to experiments such as Double Chooz [9], Daya Bay [10], and RENO [11]. Also, the DONuT experiment [12] measured the charged-current (CC) interaction cross section of the tau neutrino and tau antineutrino.

There are several reasons to consider NSI involving the (ν_τ, τ) sector. First, the third generation may be more sensitive to new physics effects because of their larger masses. Second, the constraints on NP involving the third generation leptons are somewhat weaker, allowing for larger new physics effects. The deviation of the actual mixing angle θ_{i3} from the measured one $(\theta_{i3})_{\mathrm{SM}}$, assuming the standard model cross section, can be obtained as $\delta_{i3} = \theta_{i3} - (\theta_{i3})_{\mathrm{SM}}$ for $i = 1, 2$. For example, the deviation of the measured mixing angle θ_{23} in the three processes quasielastic, Δ-resonance, and deep inelastic scattering are shown in Fig. 1. The deviation angle δ_{23} depends on the incident neutrino energy as shown. Complete results can be found in Refs. [4, 5].
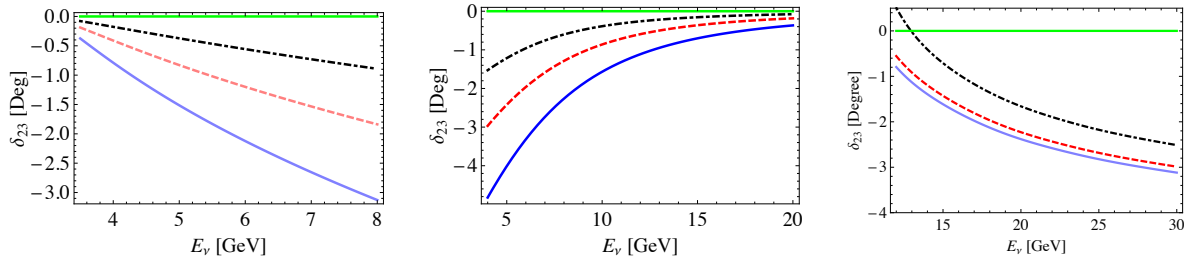
Figure 1: Variation of δ_{23} with E_ν in the QE (left) and Δ-RES (middle) in the 2HDM, and DIS (right) in the W' model. The green line corresponds to the SM prediction. The black (dotdashed), pink (dashed), and blue (solid) lines correspond to $\tan\beta = 40, 50, 60$ at $M_H = 200$ GeV (left, middle) and some representative values of the W' couplings $(g_L^{\tau\nu_\tau}, g_L^{ud}, g_R^{ud}) = (1.2335, 0.83721, 0.60636)$ at $M_{W'} = 500$ GeV (right). Here, we use the best-fit value $\theta_{23} = 42.8°$ [13].

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